EUV and X-ray observation of Abell 2199: a three-phase intracluster medium with a massive warm component

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ABSTRACT

Various independent ways of constraining the Hubble constant and the baryonic content of the universe finally converged at a consensus range of values which indicates that at the present epoch the bulk of the universe's baryons is in the form of a warm $\sim 10^6$ K gas [1,2] - a temperature regime which renders them difficult to detect. The discovery of EUV and soft X-ray excess emission from clusters of galaxies was originally interpreted as the first direct evidence for the large scale presence of such a warm component [3]. We present results from an EUVE Deep Survey (DS) observation of the rich cluster Abell 2199 in the Lex/B (69 - 190 eV) filter passband. The soft excess radial trend (SERT), shown by a plot against cluster radius r of the percentage EUV emission η observed above the level expected from the hot intracluster medium (ICM), reveals that η is a simple function of r which decreases monotonically towards $r = 0$; it smoothly turns negative at $r \sim 6$ arcmin, inwards of this radius the EUV is absorbed by cold matter with a line-of-sight column density of $\geq 2.7 \times 10^{19}$ cm^{-2}. The area of absorption is much larger than that of the cooling flow. These facts together provide strong evidence for a centrally concentrated but cluster-wide distribution of clumps of cold gas which co-exist with warm gas of similar spatial properties. Further, the simultaneous modeling of EUV and X-ray data requires a warm component even within the region of absorption. The phenomenon demonstrates a three phase ICM, with the warm phase estimated to be $\sim$ 5-10 times more massive than the hot.

The A2199 sky area was observed by EUVE for $\sim$ 57 ksec in February 1999. The programme featured an *in situ* background measurement by pointing at small offset from the cluster, which yielded an accurate background template for point-to-point subtraction

[4]. Complementary data in the X-ray (0.2 - 2.0 keV) passband, as gathered by a ROSAT PSPC observation which took place in July 1990, with an exposure of 8.5 ksec, were extracted from the public archive [5]. For correct comparison between the EUV and X-ray emissions, the Galactic HI column density was measured at $N_H = (8.3 \pm 1.0) \times 10^{19}$ cm^{-2} by a dedicated observation at Green Bank [6], and was found to be spatially smooth. The EUV and X-ray data were simultaneously modeled with a thin plasma emission code [7,8] and appropriate line-of-sight Galactic absorption [9] for the above value of N_H. At a given radius the hot ICM was assumed to be isothermal, with the abundance fixed at 0.3 solar apart from the cooling flow region where the parameter became part of the data fitting in order to account for any possible abundance gradient within this region (a different way of handling the abundance does not sensitively affect the results presented in this work).

It is found that the forementioned model, when applied to the PSPC spectra at all radii, generally leads to acceptable fits. At low energies the EUV measurements gave crucial new information. The overall effect is a soft excess as reported previously [4]. A plot of the SERT indicates, however, that the average percentage EUV excess at a given radius is less at the centre, see Figure 1. In fact, the trend takes the form of a very negative central excess (i.e. absorption), which steadily rises with radius until the 6 arcmin point, beyond which this fractional excess turns positive and continues to increase until the limiting radius of EUV detection ($\sim$ 20 arcmin [4]).

We first address the outer parts of the cluster, where the data already demonstrated the implausibility of a non-thermal interpretation of the soft excess (which postulates a large population of intracluster relativistic electrons undergoing inverse-Compton (IC) interaction with the cosmic microwave background (CMB) [10,11]). Figure 2 shows a composite plot of the EUV and X-ray data for the 12 - 15 arcmin annulus. The prominent EUV excess, unaccompanied by any similar effect in soft X-rays, implies that the bulk of the relativistic electrons have energies below 200 MeV, a cut-off which is most obviously understood as due to aging (i.e. synchrotron and inverse-Compton losses): the electrons are at least 3×10^9 years old. However, in order to account for the large EUV excess the highly evolved electron spectrum at the present epoch must still include sufficient particles ahead of the cut-off. This means that for the region of concern, at injection (when the power-law differential number index is assumed to be 2.5, in accordance with our Galactic cosmic ray index) the relativistic electron pressure would have exceeded that of the hot ICM by a factor of ~ 4, leading to a major confinement problem for the hot gas. The inclusion of cosmic ray protons exaggerates the difficulty, as protons carry 10 - 100 times more pressure than electrons. Thus, by elimination, the only viable alternative, viz. the originally proposed thermal (warm) gas scenario [3], must now be considered seriously. This is especially so in the light of the recent constraints on cosmological parameters, which point to the existence of a warm and massive baryonic component, as mentioned earlier.

To appreciate the multi-phase nature of the ICM of A2199, we move radially inwards, where Figure 1 indicates that the EUV is absorbed. For more details, we show in Figure 3 an image of the of the fractional EUV excess η. The data suggest an intermixed model [12] of the ICM: the lack of soft excess at small radii is due entirely to the larger amount of cold absorbing matter collected in this region. Thus, while in the north-south direction severe absorption persists out to a radius of ~ 4 arcmin, in the east-west direction signatures of soft excess are already present as close as $r \sim 2$ arcmin.

Our inference of the state of the ICM is reinforced by the behavior of the SERT: it follows a simple parametric profile which applies equally satisfactorily to the absorption and soft excess regions, with no change of behavior at the transition radius of ~ 6 arcmin (Figure 1). In fact, there is no particular significance in this radius (it is much larger than the cooling flow radius of ~ 2 arcmin [13]), The observation is naturally interpreted as the combined effect of clumped emission regions containing a warm component, absorbed by blobs of cold gas sandwiched in between. Both distributions are cluster-wide and centrally condensed, but with increasing radius the lines-of-sight are more transparent to EUV photons created at locations along them. For comparable intrinsic emission profiles of the soft excess and the hot ICM, the result is an outwardly rising SERT.

The correctness of this approach is confirmed by our study of the nearby Virgo and Coma clusters. In the former case a strong SERT exists despite no apparent absorption (i.e. $\eta > 0$ everywhere). Yet a spatial analysis of the PSPC image showed that a central circular area has a statistically significant enhancement in the number of small regions where the soft excess brightness is below the mean value for this circle (i.e. some of them must be due to resolved absorption clouds); with the effect disappearing gradually towards annuli of larger radius. For Coma the SERT is very weak, implying little absorption, and indeed a similar analysis revealed no evidence of clouds at any radius. Results on these two clusters will be published shortly.

The argument for an intermixed ICM also rests upon direct evidence for the presence of soft excess even in the absorbed regions. We show in Figure 4 a core spectrum, where it can be seen that by the time intrinsic absorption accounts for the EUV decrement, an excess is seen in soft X-rays (which are less absorbed). This clearly indicates a complex ICM where the various gas phases co-exist. The apparent negative soft excess within the absorption radius is simply due to an abundance of cold clouds masking EUV emissions from the warm and hot components.

The thermal origin of the EUV is compelling for another reason: the widespread absorption reported here implies the existence of a cold phase in the midst of the well known hot phase, and the question then naturally arises concerning why a warm phase is absent, and is not the cause of the soft excess. At the very least, mixing layers on the surface of the cold clouds would suffice to produce the intermediate phase [14].

The mass budgets of the three ICM components in consideration are estimated as follows. The intrinsic HI column density as inferred from the central EUV absorption converts to a density of cold clouds of $\sim 5 \times 10^{10}$ $M_\odot$ Mpc^{-3}. This gives a mass ratio of 1:2000 between the cold and hot gas along the line-of-sight. Any estimate of the mass of warm gas at the centre is likely to be inaccurate, since the soft emission is significantly absorbed. We therefore considered the 12 - 15 arcmin region where this complication is not as severe as in the center. The extreme softness of the emission (Figure 2) limits the gas temperature to kT < 100 eV (or T < 10^6 K), with a correspondingly large mass estimate of $1.25 \pm^{0.4}_{0.9} \times 10^{14}$ $M_\odot$, i.e. $\sim 43 \pm^{13}_{29}$ times more massive than the hot ICM in this region. The 1-σ lower limit ratio implies $\sim$ 3 times more missing baryons than expected [1], although it must be emphasized that both the mass and bolometric luminosity can be substantially reduced if the gas turns out to be warmer. This can be realized by adopting alternative emission models for the warm phase, especially those which involve an underionized gas, since the EUV emission efficiency is then enhanced, and the gas can be warmer than the above temperature constraint. Plasma in such an ionization state is easily produced by mixing layers or shock heating. Another possibility is that the gas is actually warmer than our inferred temperature, and the lack of a soft X-ray excess is only an apparent effect caused by residual absorption at these outer radii.

Figure Captions

Figure 1: The SERT effect illustrated by a plot against cluster radius r of the EUV fractional excess η, defined as $\eta = (p - q)/q$, where p is the DS Lex/B observed signal and q is the expected EUV emission from the hot ICM. q is determined from the best model of the PSPC data (single temperature fits were found to be satisfactory at all radii) with details of Galactic absorption as quoted in the text. The data follow a parametric profile

$\eta = -0.45 + 0.0075\, r^{2.5}$ (solid line).

Figure 2: Emission models (solid line) used to simultaneously fit the EUVE/DS and ROSAT/PSPC data of the 12 - 15 arcmin annular region of A2199. *Left Panel:* isothermal thin plasma spectrum [16-18] at kT = 4.08 keV [19] and an abundance of 0.5 solar. Note the strong EUV excess recorded by the DS (left most data point) which is not seen in soft X-rays by the PSPC (remaining data points). *Right Panel:* same as the previous model, except with an additional non-thermal component due to the IC/CMB effect (see text). The electron population (assumed to have an initial differential number index of 2.5, similar to that of Galactic cosmic rays) is $\sim$ 3.5 Gyr old, as during this period the IC/MWB and synchrotron losses would have secured the necessary high energy cut-off to avoid emissions in the PSPC passband. At the present epoch the electron pressure is $\sim$ 25 % that of the hot ICM, while the initial value of this ratio was $\sim$ 400 %.

Figure 3: An image of the surface brightness of EUV excess for the central region of Abell 2199, obtained after subtraction of background and contributions from the hot ICM emission (see text). The pixel units (color coded) are in 10^{-3} photons arcmin^{-2} s^{-1}. Pixels of negative excess correspond to areas where the EUV from warm and hot components are absorbed by a cold component. The common centroid of the cluster EUV and soft X-ray emissions is marked by a cross.

Figure 4: Data are as in Figure 2, except for the 1 – 2 arcmin radius of A2199. *Left Panel:* single temperature emission model (kT = $3.58\ \pm^{1.07}_{0.69}$, abundance = $0.56\pm^{0.43}_{0.25}$ solar) showing the EUV signal in absorption. *Right Panel:* Plasma properties as above, with an intrinsic cold gas of line-of-sight HI column density $N_H = 2.7 \times 10^{19}$ cm^{-2} invoked to account for the depleted EUV flux. Note this correction reveals a soft X-ray excess in the PSPC 1/4-keV band, thus clearly indicating the presence of an underlying warm component which is masked by the cold absorbing phase.

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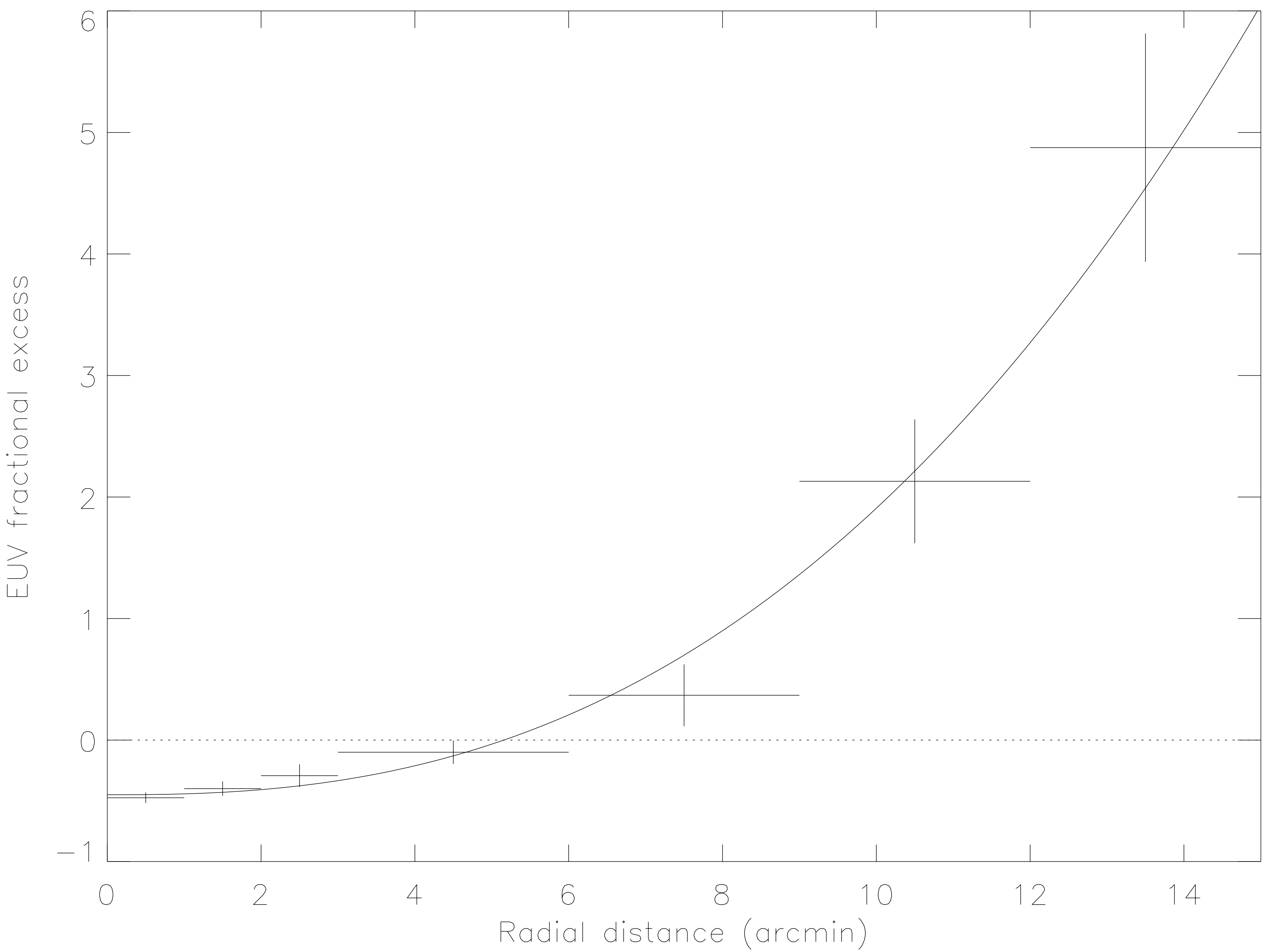
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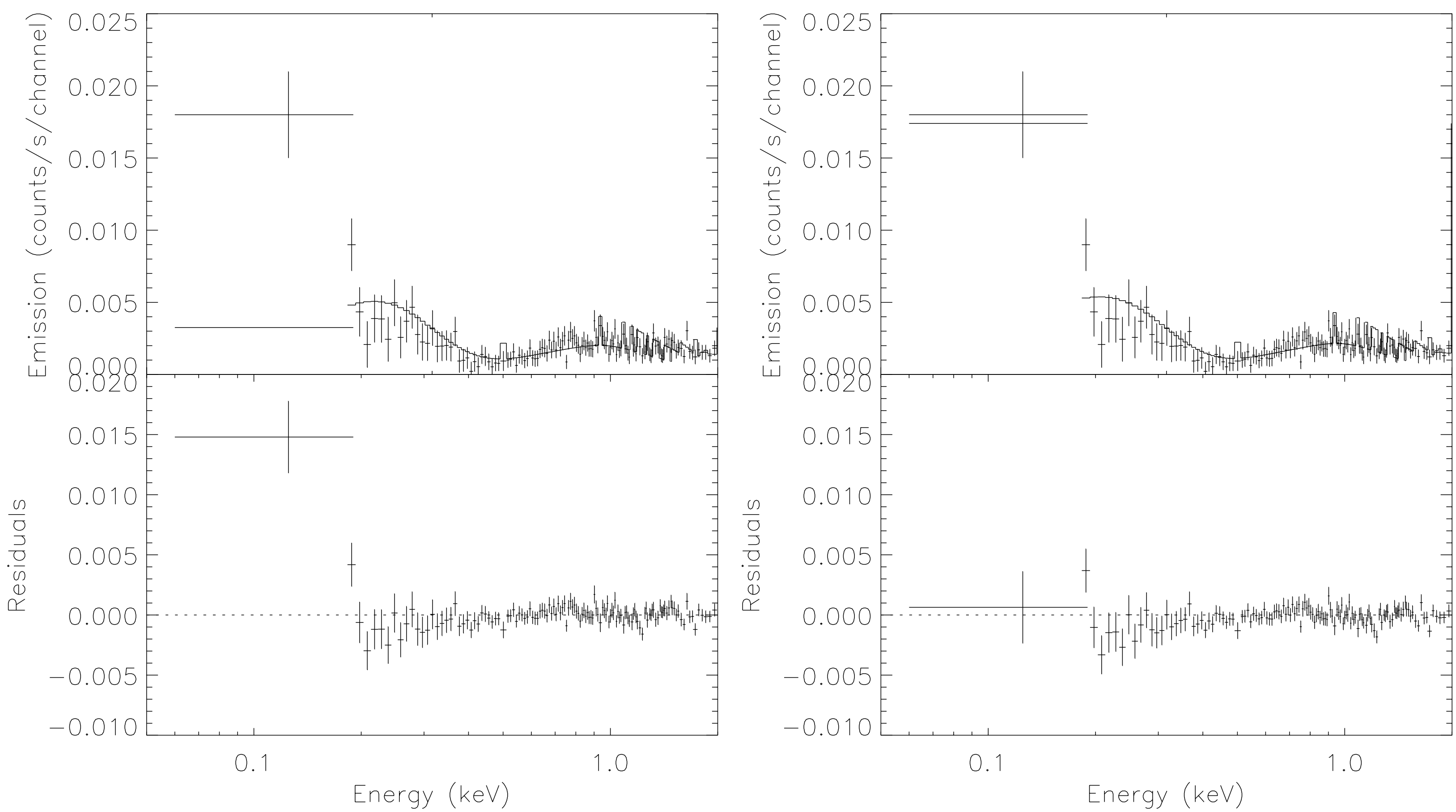
2
3
4
5
6
0
2
4
6
8
10
12
14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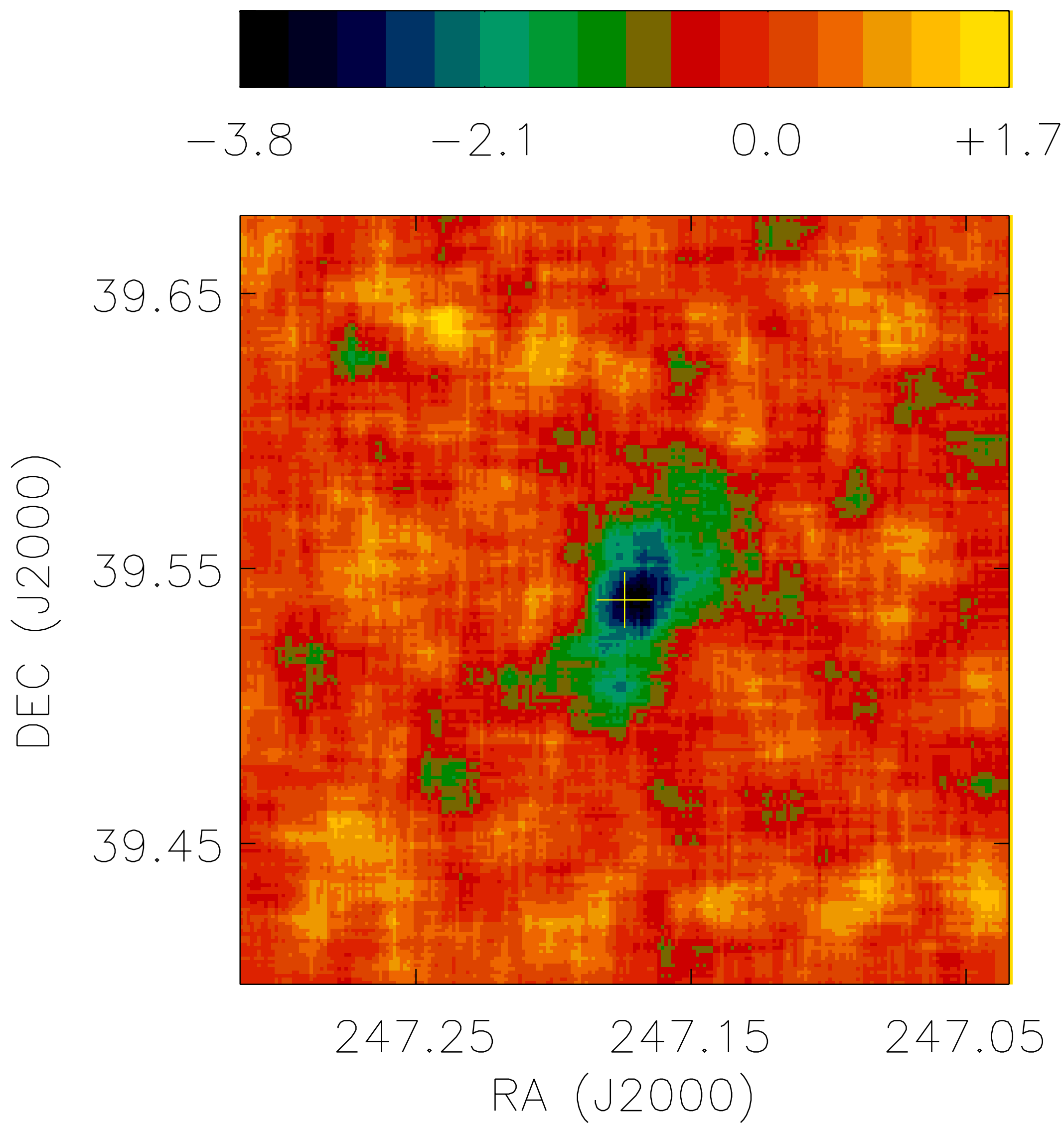
Residuals
Energy (keV)
Emission (counts/s/channel)
Residuals
Energy (keV)



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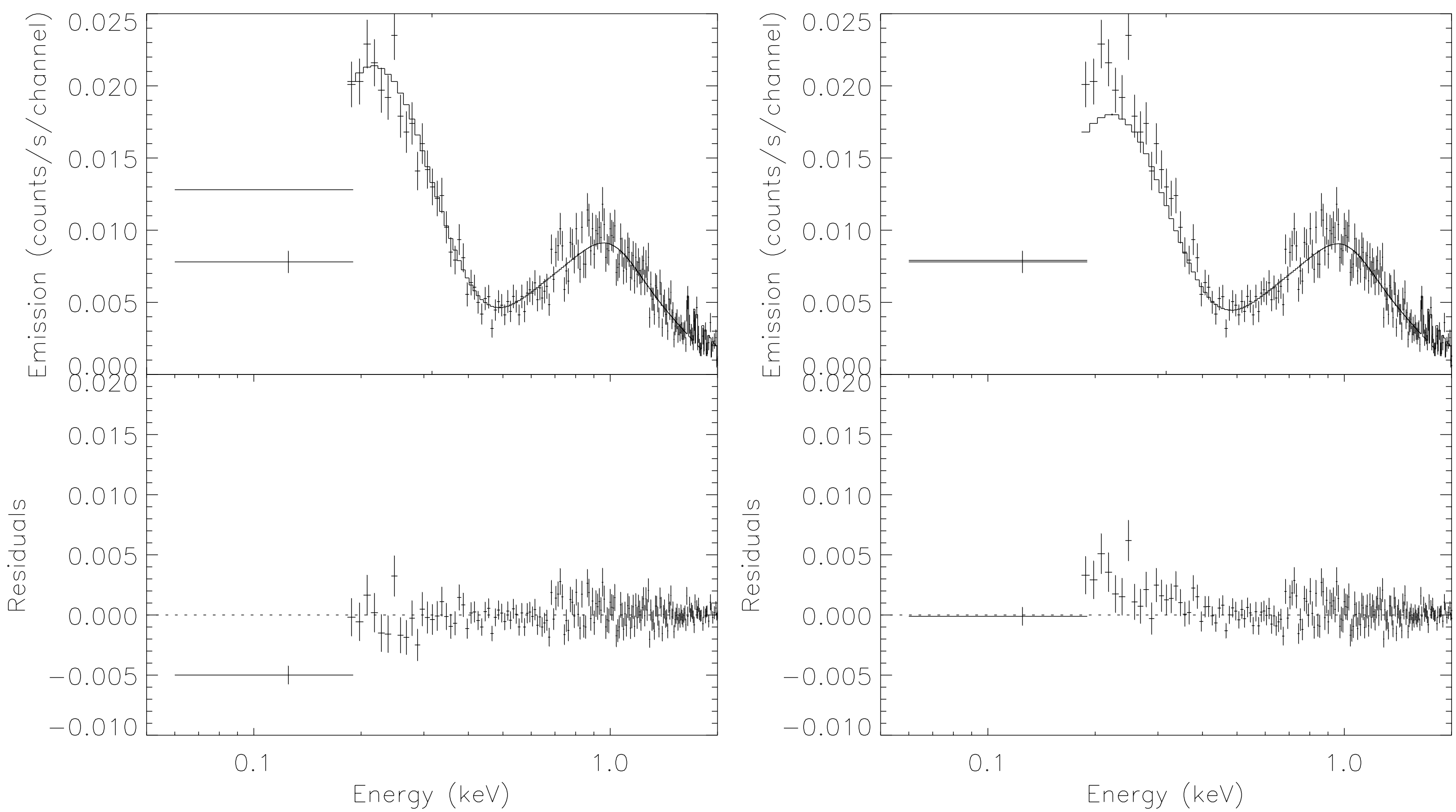

Emission (counts/s/channel)
Residuals
Energy (keV)
Emission (counts/s/channel)
Residuals
Energy (keV)